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ABSTRACT

A study was conducted to investigate the effect of various mechanical work loads on ventilation rate and heart rate, under duplicate work conditions. The task was to crank a six inch radius crank at 60 RPM against torques of O, 16, 32.1, 48 and 64.2 inch pounds equivalent to work loads of 0, 500, 1000, 1500 and 2000 ft. lb/min, respectively.

INTRODUCTION

During the past few years more research efforts have been expanded in an attempt to measure the amount of energy consumed (physiological cost) by an individual performing physical work. The energy that a person consumes can be divided into two categories. The "basal metabolic rate" is that caloric expenditure required to maintain the body in a resting state. That caloric expenditure beyond the basal metabolism is the "physiological cost" of additional work.

Measurement of energy expended can be performed by purely physical methods: (1) measure the caloric value of all food, "fuel for the combustion process," or (2) measure the work and heat produced by the combustion process. Total caloric expenditure multiplied by an efficiency factor would yield the physiological cost for a given amount of work. However, it is very complicated and difficult to evaluate the human body's combustion process and to determine the efficiency of the machinery which varies from individual to individual.

A more indirect but convenient approach is to attempt to correlate the rates of body processes that are affected by muscular activity to given work rates of activities. Heart rate, blood pressure, chemical changes, ventilation rate, body temperature, and perspiration rate are all affected by muscular activity. If a correlation between one of these processes and work rate can be determined and if an efficiency factor can be developed to account for individual discrepancies in muscle condition and size, then this body process could be monitored to determine the physiological cost of muscular activity that produces a given amount of work.

Data reported by Morehouse and Cherry (1967), which was done at the Harvard Fatigue Laboratory, indicates that in general the faster the work (in walking and carrying tasks) is done, the smaller the energy expenditure per unit of work done. It was also found that energy expenditures of more than 700 calories per hour is not maintainable except by highly conditioned athletes.

Schneider (1939) reports that the maximum heartbeat rate increases at a decreasing rate as the work load on a bicycle ergonometer is increased up to 10,000 foot pounds of mechanical work per minute. Increasing temperature or humidity above normal levels in this study was found to increase the heartbeat rate for a given task.

Katchner (1957) designed an experiment to measure the work output capabilities of people cranking at various torques with varying crank radii. In this investigation the subjects were instructed to crank as long as possible or ten minutes. The maximum work output increased for all cranks until the 50-70 inch pound torque range where the output fell off because the subjects were exhausted.

Owens and Latta (1966) used the task of turning a crank to test the heart rate as an indicator of measuring metabolic cost of doing work. They used only one cranking arrangement, and, although they concluded that heart rate could be used as a measure of metabolid cost, they realized that broader experimentation is needed.

Splinter and Suggs (1956) measured heart rate of a tractor operator performing various tasks in an effort to determine some standard of comparison by which the relative difficulty of two tasks might be determined.

Dudek and Petruno (1964) used ventilation rate in an investigation designed for the purpose of studying the physiological effects of static work loads upon the subject. The factors considered were the force or work load, the level of the shoulder beneath the grip level on the lever arm, and the degree of elbow flexion. The work load was found to have a significant effect upon the physiological cost to the operator.

Ayoub and Manuel (1966) used ventilation rate in an attempt to determine whether the criterion could be used as a physiological method of rating and performance of workers on repetitive type sedentary work. Two experiments were performed. The first was to determine if a mean level of rest could be obtained with narrow variability. The second experiment attempted to determine if a linear relationship exists between an individual's ventilation rate and the pace at which he performs a specified task.

Noud (1964) used ventilation rate to measure the physiological costs of a lever task performed when a tactile stimulus was used in a simple machine operation. The investigation showed that the stimulus had a significant effect on physiological cost.

PROCEDURE

The task in this study was to turn a crank with a six inch radius in a horizontal plane at 60 rounds per minute. The crank turned a shaft to which a 7" by 1½" by 5/8" paddle was attached. The shaft and paddle were suspended into a container which was filled with fine sand. The torque required to turn the shaft and paddle could be changed by varying the level of the sand in the container. Figure I shows the arrangement of the task described above. Subjects were tested at work loads of 0, 500, 1000, 1500 and 2000 ft. pounds of mechanical work per minute of cranking. This required 0, 16.0, 32.1, 48 and 64.2 inch pounds of torque to turn the shaft and paddle for each respective load. Since greater effort was required to start the crank moving than to maintain its motion, all calibration was done with the crank in motion at 60 rounds per minute.

Each subject cranked only at one mechanical load. Eight different subjects were tested at each of the five work loads using the two different methods of measurement. This required 40 subjects who were male volunteers from the Department of Mechanical Engineering. All subjects were between 19 and 26 years of age. All tests were performed in a controlled atmosphere to make working conditions for each test as close to being the same as possible.

For those subjects monitored with the heart rate equipment surface electrodes were attached to the subjects chest, and by means of transmitter,

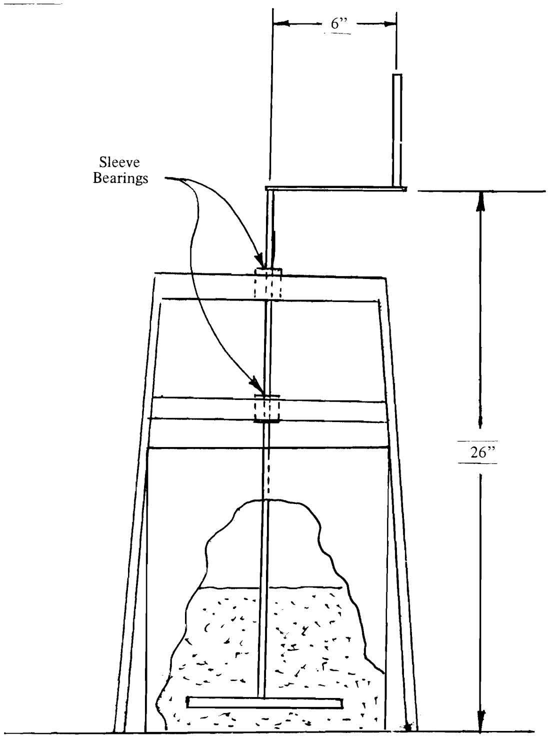

Figure 1: Crank Arrangement

receiver, amplifier, and strip chart recorder all heartbeats were recorded. The equipment used was an E-2 surface electrode, an FM1100-E-2 Telemetry Transmitter and Receiver all manufactured by the E & M Instrument Company of Houston, Texas.

For those subjects monitored with the ventilation rate equipment a respiration gas-meter connected to the subject by a flexible pleated hose fitted with a valve and face mask was used to gather the data. This equipment was manufactured by the Max Planch Institute of Work Physiology, Dortmund, West Germany.

When a subject arrived for the test he was seated on an adjustable chair, adjusted to his own liking, and given the following instructions:

> "You will grasp the crank with your hand and crank one round for each click of the metronome. The test will consist of seven cycles with one minute of cranking and one-half minute of rest. Please remain seated for ten minutes after the last cycle. I will tell you when to start and stop cranking and when the last rest period is over. Crank with your arm, keeping your body as motionless as possible."
>
> "Are there any questions?"
>
> "Crank a few turns so that you get the idea of the speed at which you must work."

The monitoring equipment was then placed on the subject and a rest period of five minutes was introduced to allow the subject to recover from any previous activity.

During the test period the heart beat was continuously monitored while the respiration meter reading was taken every minute during the pre-rest, the test, and the post-rest period.

Each subject's basal heart rate was determined from the number of heart beats during the five minutes that the heart rate was taken (before the dexterity tasks) and during the ten minutes after the last cranking. Each subject's heart beat rate was also determined for the final three cycles of cranking and resting. The heart rate while working minus the basal heart rate was the criterion for the physiological cost of performing the task. The number of heartbeats for each period was determined by enumerating the number of impulses recorded on the strip chart recorder during that period.

Each subject's basal ventilation rate was determined by averaging the last four volumetric readings of the initial and recovery rest periods in liters per minute. The last four volumes of the task period were averaged to determine the working ventilation rate. The ventilation rate while working minus the basal ventilation rate is a measure of the physiological cost of performing the task.

RESULTS

Table I shows the difference between the working rate and the base rate for those monitored with the heart rate equipment.

TABLE I

Work Loads (Ft.-lb/min.)

0	500	1000	1500	2000
2.4	20.7	9.6	24.6	52.4
4.6	11.0	11.3	15.7	25.8
3.6	2.5	5.1	16.4	35.2
-1.5	4.0	13.2	36.3	49.1

Table II shows the difference between the working rate and the base rate for those monitored with the respiration meter.

TABLE II

Work Loads (Liters/min.)

0	500	1000	1500	2000
2.0	5.5	8.3	10.8	14.8
4.0	6.9	7.5	8.0	19.7
6.2	9.1	10.1	8.4	20.2
1.0	4.0	9.9	10.0	24.3

A one-way analysis of variance was used to determine if there was a significant difference between the change in heartbeat rates at the different work loads. The results are shown in Table III.

TABLE III

Variation	d.f.	MS	F Ratio	F(.001)
Work Loads	4	2388.74	30.20	8.25
Residual	15	77.43		
Total	19			

Since the 30.20 is greater than the F(4,15,.001) = 8.25, it can be said that there is a significant difference between the change in heart rate at the different work loads at the 99.9% significance level.

Table IV shows the results of the analysis of variance for the data from the ventilation rate test.

TABLE IV

Variation	d.f.	MS	F Ratio	F(.001)
Work Loads	4	606.26	106.16	8.25
Residual	15	5.71		
Total	19			

From Table IV it can be seen that the change in ventilation at the different work loads is significant at the 99.9% level.

Table V shows the change in base heart rate and the change in base ventilation rates in percentages. This was done primarily to transform the data in a form for comparison.

TABLE V

Work Load	% Heart Rate Change	% Respiration Change
0	2.8	21.1
0	4.8	59.8
0	5.2	71.3
0	1.8	8.7
500	23.2	44.0
500	14.2	97.2
500	3.5	131.9
500	4.4	57.1
1000	11.6	116.9
1000	14.1	72.8
1000	6.0	118.8
1000	14.9	117.8
1500	22.3	157.9
1500	17.4	80.8
1500	22.9	109.1
1500	44.2	149.2
2000	58.2	154.16
2000	32.9	199.0
2000	38.7	259.0
2000	64.3	227.1

Figure II is a graph of the data found in Table V. The regression lines shown on the figure were estimated by the least squares method for the heart beat work and the ventilation work relations. The slope of the ventilation line is four times as great as the heart rate line.

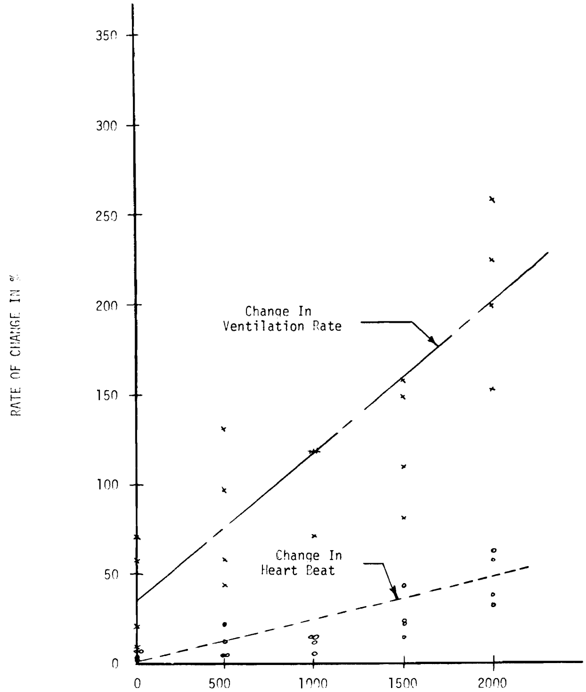

Figure 2: Work rate, Ft-lb/Minute

CONCLUSIONS

The base heart rates of the subjects had a large variance, and in some cases there was a large difference between the two base rates for an individual. It is felt that these variances are due primarily to the varying physical conditions and strength of the subjects. The base ventilation rates did not vary with individuals for the same work load as did the heart beat, which would indicate less variance in the breathing capacity of individuals than other physical attributes. Therefore, in order to obtain a more meaningful relationship for the ventilation rate among many subjects it is felt a comparative efficiency factor based possibly on size, muscle strength, or some other criteria and base rate should be developed.

From the statistical analysis it was apparent that the work load rate change was highly significant for both the heart rate analysis and the ventilation rate. The changes were significant for the linear relationship. Since the straight line relationship was significant and the high correlation coefficients were estimated, it is possible to draw some further conclusions. It was found that the rates for both heart and ventilation were on or below the regression at the 1000 and especially the 1500 ft-lb/min. range. This agrees with Katchner[3] that most cranking work can be done where the rate was about 1600 ft-lb/min. even though the average subject cannot sustain that rate for more than seven minutes.

It can be seen from Figure II that with both the ventilation rate and heart rate the rate of change increased about 5 times going from 0 work load to 200 ft-lb/minute. This would appear to lend credence to the previously alluded to fact that somehow a meaningful relationship should be obtainable for either one or both of the criteria used in this study.

In the future in addition to trying to develop a meaningful relationship between ventilation rate and other body activity it is suggested that the same type of experiment be conducted using the force platform as an effort to obtain an additional method of measuring physiological cost.

Although considerable work has been done in this area, more needs to be done in an effort to find the optimal criteria for measuring human productivity.

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